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A Study of Ignimbrites in the Cordilleran Region as a Basis for Interpretation of Lunar Plains

FINAL REPORT
covering the period June 1966-May 1975

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The research project entitled "A Study of Ignimbrites in the Cordilleran Region as a Basis for Interpretation of Lunar Plains" was initiated by J. Hoover Mackin, whose familiarity with terrestrial land forms led him to hypothesize that lunar plains (maria) were formed by flows of fragmented material in the same way that great volcanic plains are produced on earth by ash flows. He and his students expanded their study of ash flows while he began assembling photographs of lunar topographic features with the assistance of an astronomy student.

When Mackin's unexpected death interrupted the project in 1968, his colleague, W. R. Muehlberger, stepped in to assist. He proposed that NASA continue the research under his supervision on a step-funded longevity basis, which received approval in 1969. Subsequently Muehlberger accepted the full-time position of team leader for the Apollo Field Geology Investigations in January 1971 and recommended that his associate, S. E. Clabaugh, take his place as principal investigator in the ignimbrite studies. In this third-hand fashion I became directly associated with the project near the middle of its span, after the first Apollo landing had indicated that lunar plains are basalt flows, not ignimbrites. I was enthusiastic about the project because of my interest in volcanic rocks of western North America, and I wanted to see the terrestrial studies amplified and completed even if they had less-than-expected relevance to lunar deposits. I am certain that the project has made valuable contributions to our knowledge of ash flows and related rocks in Utah, west Texas, Central America and western Mexico while contributing to the research training of no fewer than 20 graduate students.

Although the scientific results are recorded in at least 20 theses and dissertations, publication of comprehensive papers has been slow, perhaps because so many of the areas selected for study were isolated and in need of additional information from adjoining areas. Half a dozen maps have been published, and some of the data have been made available in guidebooks and in a multitude of oral presentation and abstracts. Three papers are currently being reviewed for publication, and at least three more are being prepared. The "Morphological Atlas of Lunar Surface Features" assembled by Peter Schultz with initial guidance of Mackin is scheduled for publication by the University of Texas Press before the end of this year.

Stephen E. Clabaugh
July 1975

HISTORY OF THE PROJECT

In August 1965 J. Hoover Mackin, Professor of Geology at the University of Texas at Austin, submitted to NASA headquarters a proposal for support of research on ignimbrites (ash-flow deposits) as a basis for interpretation of lunar plains. Mackin was a member of the NASA Field Geology Committee and he was especially interested in lunar topography because of his own background in Geomorphology. He favored the hypothesis that the lunar plains might have been built up by flows of fragmental material "produced by major impact events, perhaps accompanied by frothing eruptive activity, and spread as density flows comparable in general with terrestrial núées ardentes." He recognized, of course, the possibilities that the flat floors of large craters might be leveled-up by flows of liquid lava or accumulations of some sort of erosional lunar dust. He observed that relatively few of the investigators of lunar surface features had first-hand knowledge of terrestrial ash-flows, and no one engaged in field work on terrestrial ash-flows was then applying his findings to lunar geology. For about 15 years previously Mackin had been working with graduate students in the eastern Great Basin where Tertiary ignimbrites are prominent, and his group was among the first to demonstrate the great areal extent of ash-flows, some of which covered more than 10,000 square miles in Utah. He proposed a three-year program of intensive study of terrestrial ignimbrites by himself, graduate students, and post-doctoral fellows with field work in the Great Basin, Texas and Mexico. He requested \$91,506 for the three-year period.

An initial grant of \$24,902 was awarded by NASA for use in the period June 1, 1966 - May 31, 1967. Supplement No. 1, amounting to \$24,984 was subsequently awarded for use in 1967-68. Mackin and his students intensified their investigations in southern Utah, and new mapping projects were begun in western Texas and the Sierra Madre Occidental of Mexico. Mackin also began to assemble an extensive collection (catalog) of photographs of lunar topographic features, with the assistance of an astronomy Ph.D. candidate.

He wrote to NASA as follows regarding the photographs on July 24, 1968: "With Peter Schultz as a research assistant, I am preparing a selection of Orbiter photographs (about 100) of lunar features, with an explanatory text appropriate to students and to the public, for publication by NASA. This project was not included in the original proposal but it fits well with it and eliminates the need for a separate contract. It was undertaken and is supervised by R. V. Wilmarth."

Mackin had almost completed a paper on lunar maria when his sudden death on August 12, 1968 brought an abrupt halt to the investigations.

Several faculty members assisted Mackin's students in completing their research projects. Most active among them was W. R. Muehlberger, department chairman, who shared Mackin's keen enthusiasm for lunar geology. Muehlberger added the finishing touches to Mackin's paper "Origin of Lunar Maria" which was promptly published in volume 80 of the Geological Society of America Bulletin (1969, pp. 735-748).

Change of Principal Investigator

Muehlberger asked in September, 1968 to be designated principal investigator for the continuation of Grant NGR 44-012-045, and in November NASA approved. In the spring of 1969, Muehlberger prepared a proposal for converting the grant to a step-funded longevity basis at a grant rate of \$24,000 per annum. He asked for a no-cost one-year extension for the unexpended funds (\$22,000) plus \$2,000 additional to be spent in 1969-70, and \$24,000 to be spent in two steps in 1970-71 and 1971-72. In August, 1969 NASA awarded the requested \$26,000 as Supplement No. 2 of Grant NGR 44-012-045 (subsequently designated NGL 44-012-045).

In his proposal Muehlberger reported briefly on the status of work in Utah, Texas and Western Mexico and indicated that compilation of the catalog of lunar photographs was continuing. He proposed additional geological studies of ignimbrites in Texas and Mexico and, in addition, mapping of volcanic rocks in central Honduras, where ash-flow deposits are also exceedingly abundant. In all of these regions he proposed to supplement the field studies with petrochemical and isotopic studies, especially K-Ar determinations for dating and correlation.

One of the investigations mentioned by Muehlberger in his 1969 proposal was a study of the Mitchell Mesa Rhyolite by E. R. Burt, a Ph.D. candidate working under the supervision of Professor S. E. Clabaugh. Burt completed his field work with the assistance of a small grant from the Geological Society of America during the summer of 1969, before the NASA grant was extended, and his stipend during preparation of the dissertation was provided by a NSF Traineeship. John Dietrich of the NASA staff at Houston served on Burt's dissertation committee and accompanied him to several field localities. The Mitchell Mesa Rhyolite is the most extensive ignimbrite in Trans-Pecos Texas, with an initial extent of more than 3000 square miles. Burt's detailed study pinpointed the Chinati Mountains, an eroded collapsed caldera, as the source of the Mitchell Mesa flow. Chemical analyses and x-ray studies of the composition and structural state of the feldspars were made by Burt, and K-Ar determinations were made on mineral separates from his samples by Dr. F. W. McDowell of the University staff.

Research in Honduras

Muehlberger supervised mapping projects done by four graduate students in Honduras during 1968-71. The work resulted in geologic maps of four quadrangles, the first to be published in that country. Doctoral dissertations were completed by J. R. Everett, R. H. Fakundiny and R. C. Finch, and a masters thesis by W. R. Duprè. The work was begun with USAID funds contracted to ICAITI. It was carried on in cooperation with the Honduran National Geographic Institute and Division of Mines and Hydrocarbons. Additional support came from the Institute of Latin American Studies and the Geology Foundation of The University of Texas. Funds from NASA Grant NGL 44-012-045 were used as a supplement to bring this cooperative project to successful completion by financing the part of the investigation most directly concerned with ignimbrites and other volcanic rocks. (The thesis by

Duprè, for example, is almost entirely volcanic geology.) Muehlberger and two students spent additional time measuring sections and correlating volcanic rocks along about 100 miles of the eastern edge of the volcanic belt where the four quadrangles are located and within a 40-mile radius of Tegucigalpa. McDowell again supplemented the field studies with K-Ar age determinations for the volcanic rocks.

Second Change of Principal Investigator

At the first Lunar Conference in Houston, Muehlberger was asked to take a more active part in the field geology training of astronauts for the Apollo flights. After gradually becoming more heavily involved in this work he requested a leave of absence from The University of Texas to become Principal Investigator (team leader) for Apollo Field Geology Investigations (under USGS contract) on a full-time basis for a period of one or two years beginning in January, 1971. In view of his departure from the University he requested in December, 1970 that the role of Principal Investigator under NASA Grant NGL 44-012-025 be transferred to Clabaugh; he proposed to remain as an associate investigator to complete the Honduran research program and the catalog of photographs of lunar features. He also requested an additional step-funded increment of \$24,000 to permit full-scale operation of the investigations in 1970-71. In February 1971 the increment was awarded as Supplement No. 3 to the grant, and the period of the grant extended through May 31, 1973.

Research in Mexico

The initial study of ignimbrites in western Mexico was made by R. B. Waitt under the supervision of Mackin and completed after Mackin's death under the supervision of Professor D. S. Barker. (Waitt sent two copies of the completed thesis to NASA headquarters early in 1971.) Barker and Clabaugh accompanied Waitt on visits to the area, and in May 1971 they reviewed Waitt's first draft of a manuscript summarizing his findings for publication (although he has not yet published it). In January 1971 new investigations of the Mexican ignimbrites were begun by three graduate students (Barrett, Fredrikson, Wahl) working under Clabaugh's supervision. A fourth student concerned mainly with isotopic studies of intrusive rocks (Henry) was supervised by Professor L. E. Long. Their field work was financed by both the NASA grant funds and the Mexican Geological Institute. The Institute provided three vehicles, their fuel and upkeep, and part of the other field expenses as well as aerial photographs and other assistance. Barrett and Wahl mapped areas along the Mazatlán-Durango highway between the two areas mapped by Waitt in his initial study. Fredrikson and Henry did reconnaissance mapping of a large area extending from Mazatlán north and east across Sinaloa to join Waitt's western area.

Three additional graduate students (Keizer, Lyons, Swanson) subsequently mapped an area of several hundred square kilometers surrounding the city of Durango at the eastern edge of the Sierra Madre Occidental volcanic field. Again the Instituto de Geología provided some assistance in Mexico and one field vehicle, while the NASA grant supported petrographic studies, K-Ar age determinations, chemical analyses and manuscript preparation. Clabaugh supervised

the geologic mapping, and McDowell guided Keizer's K-Ar measurements. One manuscript by the three students and Clabaugh describing the volcanic stratigraphy of the Durango area has been completed and another by Keizer and McDowell discussing the K-Ar ages of the volcanic rocks near Durango and farther southwest is almost complete. Mapping disclosed a very large resurgent caldera with its center about 10 km north of Durango (in the area where many John Wayne movies have been filmed). One of Mexico's major iron deposits, Cerro de Mercado, is a complex volcanic mound of magnetite flows, dikes and pneumatolytic deposits within the caldera fill. Associated with the iron deposit is a widespread sheet of very fine-grained hematite crystals which we interpret as an ash deposit, the first ever reported composed of iron oxide.

In October 1971 the Instituto de Geología and The University of Texas jointly sponsored a colloquium at the National University in Mexico City on the geology of western Mexico (especially Sinaloa), followed by a field trip led by Clabaugh in the Durango-Mazatlán region. For the meeting of the Sociedad Geológica Mexicana in May 1972 Clabaugh again led a field trip and compiled a field trip guide that was published in the Memoria volume. Papers by McDowell, Clabaugh and four students were presented in formal sessions of the meeting.

Research in West Texas

Field studies of ignimbrites in West Texas were resumed under Clabaugh's direction in 1970-71, and they were coordinated with studies of related intrusive igneous rocks supervised by Barker and Long (involving Sr isotope ratios and Rb-Sr determinations) and with volcanic rock dating and correlation by McDowell (using K-Ar determinations). One graduate student (Parker) began mapping a key area in the northern part of the Davis Mountains in 1970, and another student (Smith) began mapping an adjacent area in the summer of 1971. Parker and McDowell have prepared a manuscript on the age of volcanic rocks in the northern Davis Mountains which is now being submitted for the publication.

In March 1971 Clabaugh requested an additional supplement in order to continue the project at the same level in 1971-72. Supplement No. 4 was awarded in June 1971; it added \$24,000 to the grant funds and extended the period of the grant through May 31, 1974. Supplement No. 5, also for \$24,000, was requested and awarded in 1972, which permitted the project to continue with full funding through May 31, 1973, and with successively smaller steps through May 31, 1975, when all funds were exhausted.

The two students (Parker, Smith) who began mapping in the Davis Mountains in 1970 and 1971 completed their field work during 1972, and two additional mapping projects were initiated under Clabaugh's supervision in other parts of west Texas in 1973. One of these (by Hatcher) is an investigation of the pyroclastic rocks, dikes and lava flows northwest of Agua Fria Mountain; the other (by Cepeda) is a restudy of the Chinati Mountains, which has been recognized in recent

years as a deeply eroded and very large caldera. K-Ar age determinations are of special importance in both areas; the Agua Fria area is a prolific source of early Tertiary vertebrate fossils, and the Chinati caldera supplied the widespread Mitchell Mesa Rhyolite as well as several major undated ash flows within the caldera collapse zone.

Completion and Presentation of Results

Many of the expenditures of the final two or three years have been for completion of research begun earlier under the grant. This has involved part-time stipends for research assistants making petrographic studies, preparing thin sections and mineral separates, assisting with K-Ar determinations, compiling and drafting maps, and writing the theses, dissertations, and research reports that resulted from investigations. It should be emphasized that a major and steadily increasing amount of support for the research has also been provided by the University. A machine shop and machinist, a thin-section laboratory and technician, a chemist to make rock and mineral analyses, and equipment for K-Ar determinations with a new staff member to direct the work (McDowell) have all been added since Mackin originally submitted his proposal. Very recently we purchased the electron microprobe formerly used at Cal Tech (where it was originally acquired with NASA funds, I believe); we have a scanning electron microscope that is proving useful in examining feldspars from ignimbrites, and we recently assembled a mass spectrometer for stable isotope studies. All of the supporting technical staff are paid by the University from non-grant funds, but the existence of this and other grants has obviously spurred the development of our facilities. The department has a non-profit, fund-raising organization called the Geology Foundation which has provided part of the support of nearly all graduate students working on the ignimbrite project as well as part of the faculty travel funds and some funds for typing reports and drafting maps.

In anticipation of the termination of NASA funding for the ignimbrite studies Clabaugh and McDowell submitted a proposal to NSF for a two-year grant to continue investigation of Tertiary volcanic rocks in western Mexico, and it was awarded in the fall of 1973. (Additional NSF funding for 1976-77 has also been requested.) The strength of these NSF proposals stems from the accomplishments of the earlier research supported by the NASA grant.

Interest in the Sierra Madre Occidental volcanic province was brought into focus by the symposium on "The Geology of the Sierra Madre Occidental and Adjoining Regions" organized by Clabaugh and McDowell for the South-Central Sectional Meeting of the Geological Society of America in Austin on March 13-14, 1975. (This two-day symposium drew standing-room-only attendance; it was the most popular event of the meeting.) At least six of the papers were based in part on the results of research financed by the NASA grant for ignimbrite studies. Three papers presented in 1973 at the National GSA meeting in Dallas, two presented in 1974 at the convention of the Sociedad Geologica Mexicana in Guanajuato, and two presented in 1974 in Honduras at the Central American Geological Meeting were also products of research supported by this grant.

Lunar Atlas

The compilation of photographs of lunar topographic features and the preparation of an explanatory text begun by Mackin in 1968 with the assistance of Peter Schultz resulted in a 600-page atlas completed by Schultz as his dissertation for the Ph.D. degree in Astronomy in 1972. In July 1972 NASA headquarters approved an extension of the grant to cover a direct subvention of \$20,000 to the University of Texas Press to pay part of the cost of publishing the atlas as a high-quality printing job (pictures to be 300-line offset, Meriden Gravure Co., on superior paper). No new funds were provided for this purpose; the money to be used had resided in the grant since approximately the time of Mackin's unexpected death. The University of Texas Press agreed to pay for the additional production costs, editing, promotion, storage, selling, shipping and reprinting if demand justifies it. The Press has announced publication of the book with the title Moon Morphology in the fall of 1975.

The NASA Technical Officer for this grant during most of its duration was Robert P. Bryson. He was replaced by Jack B. Hanley in 1974, and following Hanley's death in 1975, Desiree E. Stuart-Alexander assumed his duties as technical monitor on the grant.

PUBLICATIONS, MANUSCRIPTS, DISSERTATIONS
AND THESES PREPARED WITH SUPPORT FROM
NASA RESEARCH GRANT NGL 44-012-045

Note: All dissertations and theses in this list were prepared at The University of Texas at Austin, and copies of them may be examined there.

Group I; initiated by J. H. Mackin:

1. McKnight, J. F. (1968) Geology of Bofecillos Mountains area, Trans-Pecos Texas: unpub. Ph.D. dissertation.
2. Rowley, P. D. (1968) Geology of the Southern Sevier Plateau, Utah: unpub. Ph.D. dissertation.
3. Mackin, J. H. (1969) Origin of Lunar Maria: Geol. Soc. America Bull., v. 80, p. 735-748.
4. McKnight, J. F. (1970) Geology of Bofecillos Mountains area, Trans-Pecos Texas: Univ. Texas, Bur. Econ. Geol. Quad. Map. No. 37, 36-p. text.
5. Waitt, R. B. (1970) Ignimbrites of the Sierra Madre Occidental between Durango and Mazatlán, Mexico: unpub. M.A. thesis.
6. Waitt, R. B. (1971 manuscript) Late Tertiary ash-flow tuffs in the Sierra Madre Occidental between Durango and Mazatlán, Mexico.
7. Schultz, P. H. (1972) Morphological Atlas of Lunar Surface Features: unpub. Ph.D. dissertation.
8. Schultz, P. H. (1975 planned) Moon Morphology: University of Texas Press, c. 626 p., 268 photographs.

Group II; initiated by W. R. Muehlberger:

9. Dupré, W. R. (1970) Geology of the Zambrano Quadrangle, Honduras, Central America: unpub. M.A. thesis.
10. Everett, J. R. (1970) Geology of the Comayagua Quadrangle, Honduras, Central America: unpub. Ph.D. dissertation.
11. Fakundiny, R. H. (1970) Geology of the El Rosario Quadrangle, Honduras, Central America: unpub. Ph.D. dissertation.
12. Everett, J. R. (1970) Mapa Geológico de Comayagua, Honduras: Tegucigalpa, Inst. Geog. Nac. Hoja 2659 II G.

13. Fakundiny, R. H. (1971) Mapa Geológico de El Rosario, Honduras: Tegucigalpa, Inst. Geog. Nac., Hoja 2659 I G.

14. Finch, R. C. (1972) Geology of the San Pedro Zacapa Quadrangle, Honduras, Central America: unpub. Ph.D. dissertation.

15. and 16. Maps of the Zambrano (Dupré) and San Pedro Zacapa (Finch) Quadrangles have presumably been published in Honduras or will be.

Group III; initiated by S. E. Clabaugh:

17. Burt, E. R. (1970) Petrology of the Mitchell Mesa Rhyolite, Trans-Pecos Texas: unpub. Ph.D. dissertation.

18. Clabaugh, S. E. (1972) Geologic road log, Durango-Mazatlán: Sociedad Geologica Mexicana IIa Convencion Nacional Memoria, pp. 80-96.

19. Henry, C. D. (1972) K-Ar Chronology of the Granitic Batholithic Complex, Sinaloa, Mexico: unpub. M.A. thesis.

20. Parker, D. F. (1972) Stratigraphy, petrography and K-Ar geochronology of volcanic rocks, northeastern Davis Mountains, Trans-Pecos Texas: unpub. M.A. thesis.

21. Fredrikson, G. (1973) Geology of the Mazatlán area, Sinaloa, western Mexico: unpub. Ph.D. dissertation.

22. Keizer, R. P. (1973) Volcanic stratigraphy, structural geology and K-Ar geochronology of the Durango area, Durango, Mexico: unpub. M.A. thesis.

23. Wahl, D. E. (1973) Geology of the El Salto strip, Durango, Mexico: unpub. M.A. thesis.

24. Swanson, E. R. (1974) Petrology and volcanic stratigraphy of the Durango area, Durango, Mexico: unpub. M.A. thesis.

25. Henry, C. D. (1975) Geology and geochronology of the granitic batholithic complex, Sinaloa, Mexico: unpub. Ph.D. dissertation.

26. Lyons, J. I. (1975) Volcanogenic iron ore of Cerro de Mercado and its setting within the Chupaderos Caldera, Durango, Mexico: unpub. M.A. thesis.

27. Smith, M. A. (1975) Geology and trace element geochemistry of the Fort Davis area, Trans-Pecos Texas: unpub. Ph.D. dissertation.

28. Barrett, T. W. (in preparation) Geology of the La Ciudad strip, Durango, Mexico: unpub. M.A. thesis.

29. Cepeda, J. C. (in progress, mapping nearly completed) Geology and geochemistry of the Tertiary volcanic rocks of the Chinati Mountains, Presidio County, Texas: unpub. Ph.D. dissertation.

30. Hatcher, G. D. (in preparation) Stratigraphy and petrology of igneous rocks of the Agua Fria area, west Texas: unpub. M.A. thesis.
31. McDowell, F. W. and Keizer, R. P. (manuscript) Mid-Tertiary volcanism in the Sierra Madre Occidental near Durango City, Mexico.
32. Parker, D. F. and McDowell, F. W. (manuscript) Stratigraphy and K-Ar geochronology of Oligocene volcanic rocks, Davis and Barilla Mountains, Trans-Pecos Texas.
33. Swanson, E. R. (in progress, mapping nearly completed) Geology of the Temóchic area, Chihuahua, Mexico: unpub. Ph.D. dissertation.
34. Swanson, E. R.; Keizer, R. P.; Lyons, J. I.; and Clabaugh, S. E. (manuscript) Tertiary volcanism and caldera development in the Durango City Area, Sierra Madre Occidental, Mexico.
- 35.--Henry and Lyons are each preparing manuscripts for publication based on their theses listed above. Cepeda's work will probably be published by the University of Texas Bureau of Economic Geology.

Published abstracts of papers presented orally at scientific meetings are not listed above.